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Energy management strategy based on fuzzy logic for a fuel cell hybrid bus

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ABSTRACT

Fuel cell vehicles, as a substitute for internal-combustion-engine vehicles, have become a research hotspot for most automobile manufacturers all over the world. Fuel cell systems have disadvantages, such as high cost, slow response and no regenerative energy recovery during braking; hybridization can be a solution to these drawbacks. This paper presents a fuel cell hybrid bus which is equipped with a fuel cell system and two energy storage devices, i.e., a battery and an ultracapacitor. An energy management strategy based on fuzzy logic, which is employed to control the power flow of the vehicular power train, is described. This strategy is capable of determining the desired output power of the fuel cell system, battery and ultracapacitor according to the propulsion power and recuperated braking power. Some tests to verify the strategy were developed, and the results of the tests show the effectiveness of the proposed energy management strategy and the good performance of the fuel cell hybrid bus.

1. Introduction

Air pollution, dependence on oil, and greenhouse gas emissions are problems that are inherent in internal-combustion-engine vehicles. Fuel cell vehicles have been proposed as a potential solution in the case of automobiles [1–3]. But a fuel cell system alone, integrated into a vehicular power train, is not always sufficient to supply propulsion power for a vehicle, because fuel cell systems have some deficiencies, such as high cost, slow response and no regenerative energy recovery during braking. Hybridization of a fuel cell system with energy storage devices can be a solution to these drawbacks. One motivation for hybridization is that energy storage devices can provide instant peak power during transient conditions of vehicle operation and improve fuel economy by taking advantage of regenerative braking power; at the same time, hybridization can also be helpful in decreasing the cost of the vehicle because of the possibility to use a smaller fuel cell system. Two kind of energy storage devices that can be used for the purpose of hybridization are a battery and an ultracapacitor [4,5].

Usually, hybridization of a fuel cell system and a battery or hybridization of a fuel cell system and an ultracapacitor is chosen and the relative studies have been described in Refs. [6,7]. But using both a battery and an ultracapacitor together can provide a powerful energy storage system with the merits of both high energy density and high power density, which is significant for fuel cell vehicles.

The resulting combination of three power sources, namely a fuel cell system, a battery and an ultracapacitor, in a fuel cell hybrid vehicle is complicated, and the energy management strategy plays an important role in controlling the distribution of power among the power sources. It has been demonstrated that a fuzzy controller is very effective for optimally distributing the power in a fuel cell vehicular hybrid power train on the basis of the experimental knowledge [8–11]. In this paper, fuzzy logic has been employed for the energy management strategy of a fuel cell hybrid bus. Some tests were carried out, and the results show the effectiveness of the proposed energy management strategy, and good performance of the fuel cell hybrid bus.

2. Power train of the fuel cell hybrid bus

2.1. The fuel cell hybrid bus

The fuel cell hybrid bus described in this paper is shown in Fig. 1. The bus is 11 m long, 2.5 m wide and 3.4 m high, and can carry 50 passengers. Its maximum speed is 80 km h^{-1}, and its gross mass is 14,200 kg.

2.2. The fuel cell hybrid power train

Fig. 2 shows the configuration of the power train of the fuel cell hybrid bus. The hybrid power train consists of a fuel cell system, a

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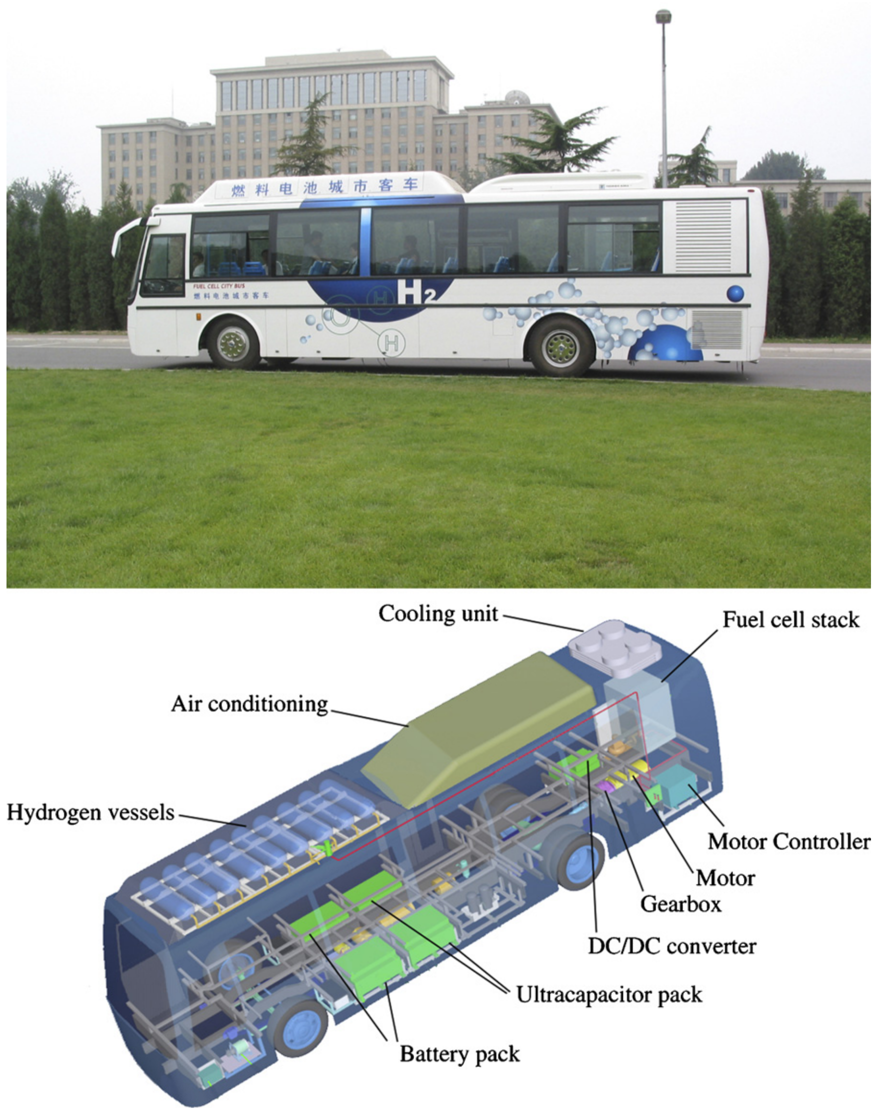

Fig. 1. Fuel cell hybrid bus.

battery pack, an ultracapacitor pack, a motor inverter, an induction motor, a unidirectional dc/dc converter and a bidirectional dc/dc converter. The fuel cell system supplies the power to the load via the unidirectional dc/dc converter, and the ultracapacitor pack is connected to the dc voltage bus via the bidirectional dc/dc converter; in addition, the battery pack is connected directly to the dc voltage bus. The specifications of the fuel cell hybrid power train are shown in Table 1.

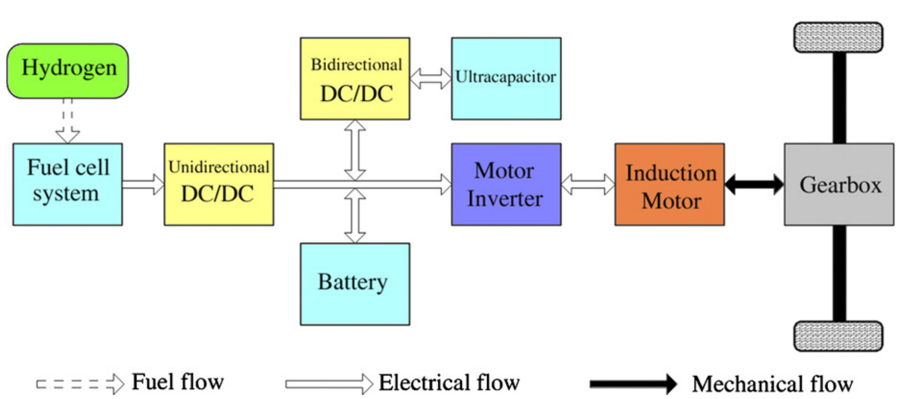

Fig. 2. Power train of the fuel cell hybrid bus.

Table 1
Specifications of the fuel cell hybrid power train

Fuel cell system	
PEM stacks	2 × 504 cells
Output voltage	330–500 V
Output power (net)	65 kW
Cooling mode	Water
Hydrogen vessels	
Pressure	200 bar
Volume	9 × 100 l
Battery	
Type	Valve-regulated lead acid
Capacity	24 Ah
No. of modules	28
Nominal voltage	336 V
Cooling mode	Air
Ultracapacitor	
Capacity	3500 F
No. of modules	144
Maximum voltage	390 V
Cooling mode	Air
Unidirectional dc/dc converter	
Type	Buck
Input voltage	320–550 V
Output voltage	280–400 V
Maximum output current	240 A
Cooling mode	Water
Bidirectional dc/dc converter	
high-voltage side	
Voltage	280–400 V
Maximum current	300 A
Low-voltage side	
Voltage	180–390 V
Maximum current	450 A
Cooling mode	Water
Motor inverter	
Input voltage	280–420 V
Control mode	Vector control
Cooling mode	Water
Motor	
Type	Induction
Maximum output power	120 kW
Maximum output torque	650 N m
Cooling mode	Water

3. Energy management strategy

3.1. Description

An energy management strategy was used to control the distribution of power among the power sources in the proposed fuel cell hybrid power train. As shown in Fig. 2, a unidirectional dc/dc converter was employed to transfer the desired power from the fuel cell system to the power train. Therefore, not only did the higher output voltage of the fuel cell system decline to a voltage that matched the motor inverter, but the slow power response, which is considered as a disadvantage of fuel cell systems, could be made less of a

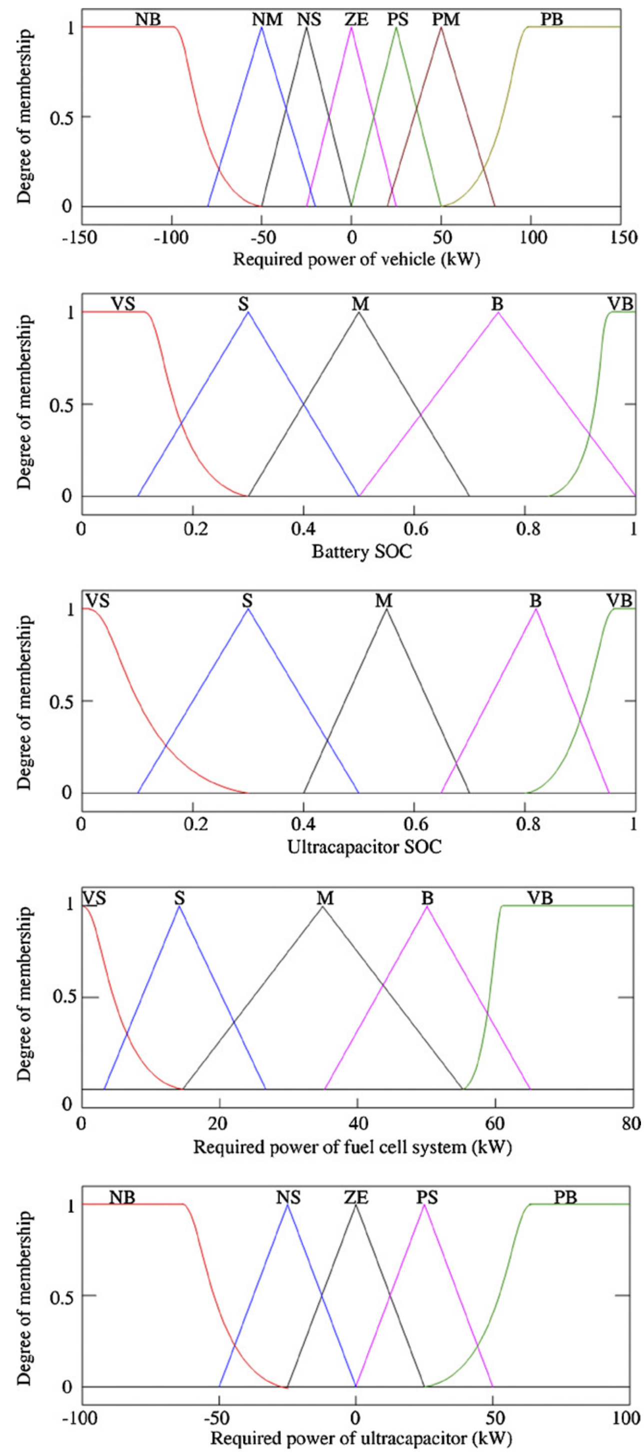

Fig. 4. Membership functions of input and output variables.

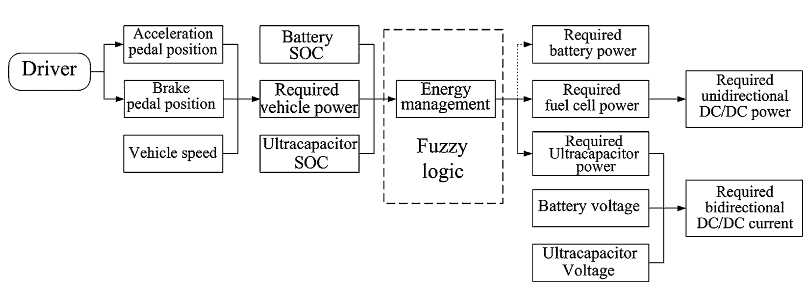

Fig. 3. Basic control structure of the power train.

problem. In addition, an ultracapacitor was decoupled to the power train using a bidirectional dc/dc converter, which could control the charging or discharging of the ultracapacitor. Usually, a dc/dc converter, which is a power electronics device, can operate in three modes, namely current control mode, voltage control mode and power control mode, where the output current, the output voltage and the output power, respectively, are controlled. In the work described in this paper, the unidirectional dc/dc converter operated in power mode, but the bidirectional converter operated in current mode. So, the three power sources in the power train can be divided into two kinds: two active-control power sources, where the output power is controlled directly, were used with the fuel cell system and the ultracapacitor; and a passive-control power source, where the output power is controlled indirectly, was used with the battery.

The basic control structure of the power train of the fuel cell hybrid bus is shown in Fig. 3. The distribution of power among the fuel cell system, the battery and the ultracapacitor is determined by calculating the required power for the propulsion of the vehicle, taking account of the state of charge (SOC) of the battery and of the ultracapacitor. When the required power for the bus is high, the fuel cell system, the battery and the ultracapacitor should supply power to the vehicle simultaneously, however, when the required power is medium or low, the distribution of power among the three power sources is complex, and depends on the battery SOC and the ultracapacitor SOC; correspondingly, the battery and the ultracapacitor can be charged or discharged. In order to achieve a more efficient power distribution, the fuel cell system should operate in a high-efficiency region and the battery SOC should be maintained at a reasonable level.

3.2. Fuzzy logic

The power train of the fuel cell hybrid bus presented here is complex and has several variables, and therefore fuzzy logic is suitable for the energy management strategy.

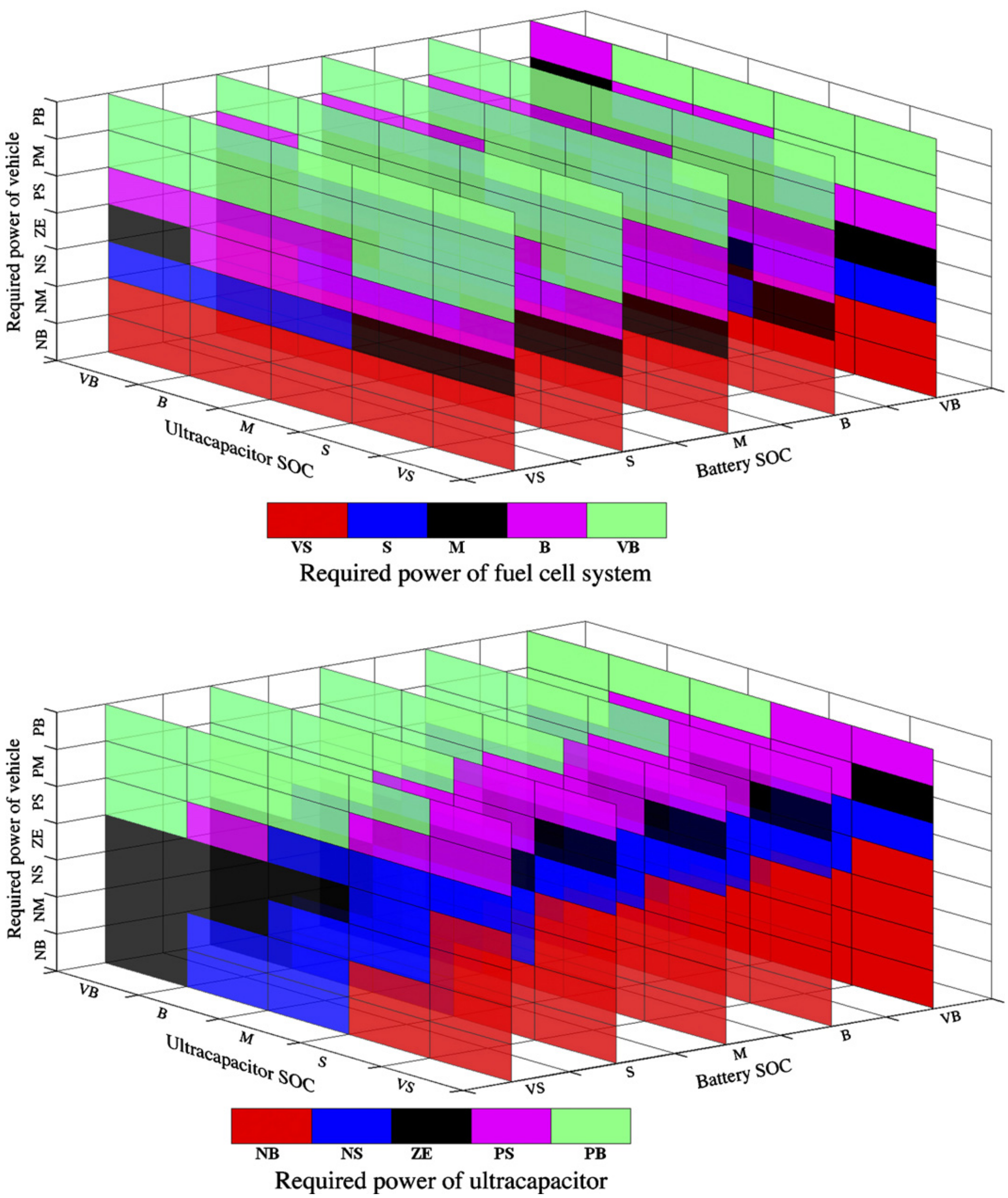

Fig. 5. Rule base of the fuzzy logic controller.

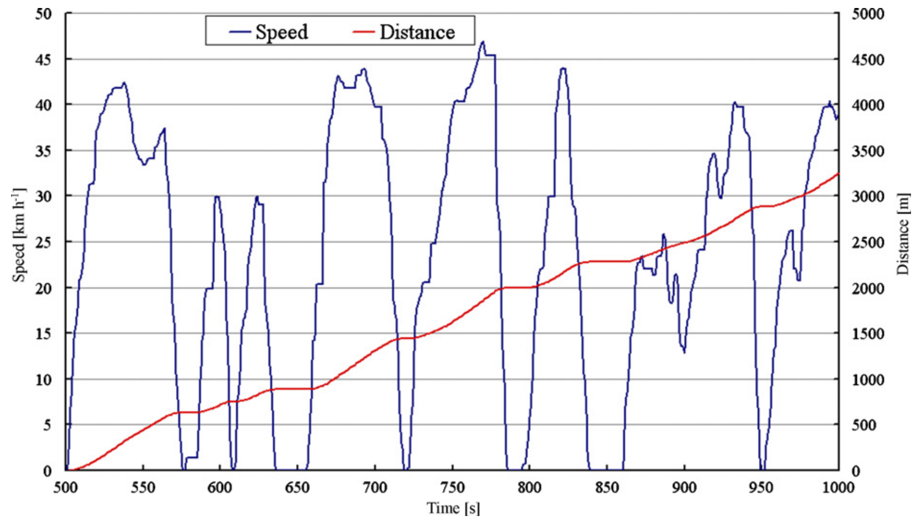

Fig. 6. A portion (500 s) of a drive cycle of a regular bus route in Beijing.

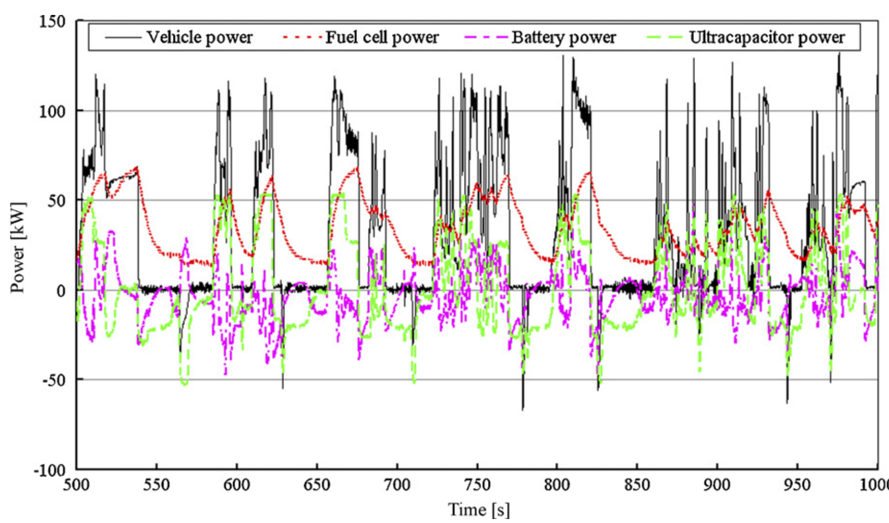

Fig. 7. Power distribution for the power train of the fuel cell hybrid bus.

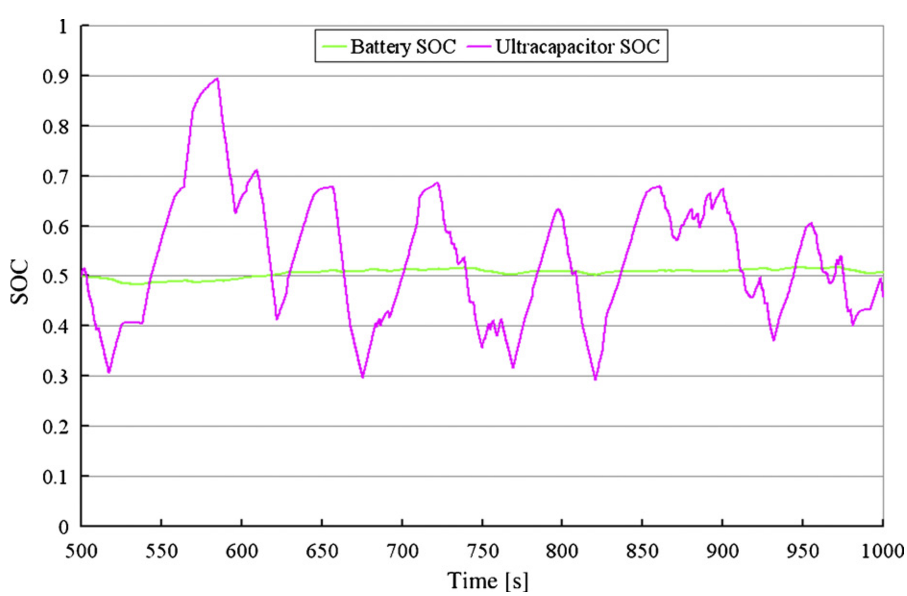

Fig. 8. Test results for the SOCs of the battery and ultracapacitor.

Fuzzy logic controller relates the controller output to the inputs using a list of IF–THEN rules. A fuzzy IF–THEN rule is an IF–THEN statement in which some words are characterized by continuous membership functions. The IF part of a rule, called the antecedent, specifies the condition (i.e., the combination of inputs) for which a rule holds. The THEN part of a rule, called the consequent, refers to values of the output variable. To obtain the output of the controller, the degrees of membership of the IF parts of all rules are evaluated, and the THEN parts of all rules are averaged, weighted by these degrees of membership (see Ref. [12] for more information on fuzzy logic controller). Fuzzy logic controller is especially very suitable for processes with complex models.

The fuzzy logic controller in this study has three input variables and two output variables. The input variables are the power required for the bus, the battery SOC and the ultracapacitor SOC. The output variables are the power required from the fuel cell system and the power required from the ultracapacitor. The power required from the battery can be calculated by subtracting the power required from the fuel cell system and the power required from the ultracapacitor from the total power required by the bus.

The performance of an energy management strategy based on fuzzy logic is determined by the number and shape of the membership functions of each fuzzy variable, and by the selection of rules, which are essential for increasing the vehicle efficiency and for maintaining the battery SOC and ultracapacitor SOC. The membership functions of the input and output variables are shown in Fig. 4. The specification of the rules of the fuzzy logic controller depends on the designer knowledge about the supplies and traction device constraints; intuitive and practical aspects regarding the propulsion mechanism dynamic behavior; and successive experiments to assure the process's robustness and reliability [11]. The rule base is shown in Fig. 5. For example, if the required power of the bus is "PB" (positive big), the battery SOC is "M" (medium) and the ultracapacitor SOC is "VB" (very big), then the required power of the fuel cell system is "VB", and the required power of the ultracapacitor is "PB".

4. Validation and analysis

4.1. Validation of the control strategy

To evaluate the performance of the proposed energy management strategy and the performance of the bus, some tests were carried out on a regular bus route from Beigongmen to Xiyuan in Beijing. A short period (500 s) of the drive cycle is shown in Fig. 6. Figs. 7 and 8 show the test results for the fuel cell hybrid bus, where the power train was controlled by the energy strategy based on fuzzy logic proposed in this paper. In order to reduce the demands on the response of the fuel cell system, the control of the unidirectional dc/dc power converter should operate via a delay unit, and then the output power of the fuel cell system can change slowly and gradually.

Table 2
Summary of data for the 500 s drive cycle

Distance (m)	3249
Duration (s)	500
Average speed (km h^{-1})	46.8
Maximum speed (km h^{-1})	23.4
Fuel cell system energy (Wh)	4794.9
Battery energy (Wh)	−455.1
Ultracapacitor energy (Wh)	71.8
Braking energy (Wh)	−136.8
Energy consumption by accessories (Wh)	416.7
Motor traction energy (ac) (Wh)	4131.7
Hydrogen consumption (g)	259.3

As shown in Fig. 7, the fuel cell hybrid bus with energy management based on fuzzy logic shows a good distribution of power among the fuel cell system, the battery and the ultracapacitor, for the purpose of providing the required power to drive the bus. From Figs. 7 and 8, it can be seen that the SOCs of the battery and ultracapacitor can be maintained in a reasonable range, and also that the output power of the fuel cell system is maintained mainly between 15 and 65 kW.

4.2. Hydrogen consumption and efficiency

Fig. 9 shows the efficiency of the fuel cell system for the fuel cell hybrid bus. As a result of the energy management based on fuzzy logic, the output power of the fuel cell system was in a high-efficiency region during the 500 s drive cycle. Table 2 shows a summary of data related to consumption and efficiency. The hydrogen consumption during the drive cycle was 259.3 g, i.e., the fuel consumption of the bus was 7.98 kg H_2 $(100\ km)^{-1}$, which could be improved by increasing the recovery of braking energy. But it should be pointed out that the air conditioning of the bus was turned off during the drive cycle; air conditioning has an important effect on the fuel economy of a vehicle.

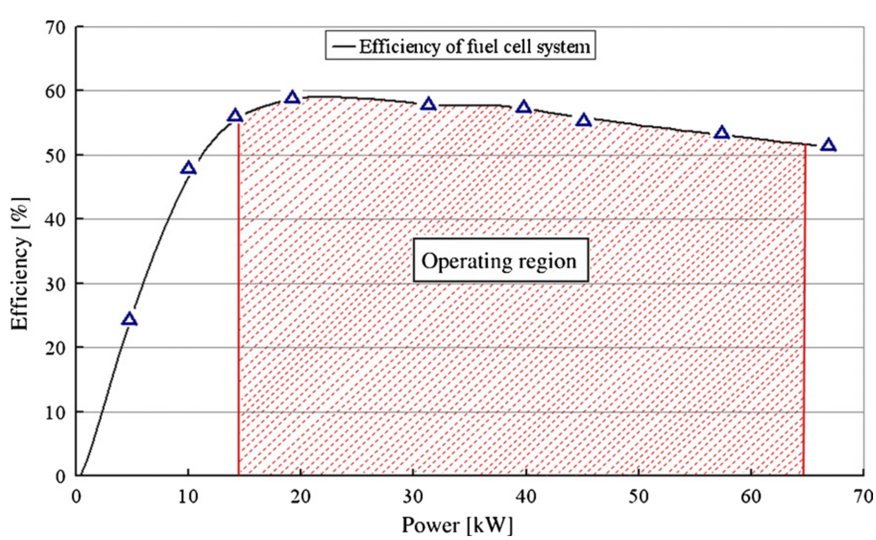

Fig. 9. Efficiency map and operating region of the fuel cell system.

5. Conclusions

In this paper, we have presented a fuel cell hybrid bus, the power train of which includes three power sources, namely a fuel cell system, a battery and an ultracapacitor. Because of the complexity of the power train, fuzzy logic was developed and implemented to manage the energy flow.

To evaluate the performance of the proposed energy management strategy and of the bus, some tests have been carried out on a regular bus route in Beijing. We have given some results, which show that the fuel cell hybrid bus has good efficiency; in addition, the energy management and the distribution of power among the three power sources are reasonable.

Acknowledgment

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